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AWE Experiments on Laser-Driven Mix in Planar and Convergent Geometry

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Abstract: AWE has had an active laser experimental program studying the physics of compressible turbulent mix for many years. Here we report on progress using the HELEN and OMEGA laser facilities. Recent work on HELEN has centred around obtaining well characterised data on shock-induced mixing at a foam-foam interface of varying roughness. A thin, opaque tracer layer is used as a radiographic diagnostic to determine mix widths. Use of OMEGA has allowed us to investigate mix evolution directly in convergent geometry in a compressible plasma regime for the first time. The experiments comprise a plastic cylindrical shell imploded by direct laser irradiation. The cylindrical shell surrounds a lower density plastic foam which provides sufficient back pressure to allow the implosion to stagnate at a sufficiently high radius to permit quantitative radiographic diagnosis of the interface evolution near turnaround. The Atwood number of the shell-foam interface is varied by choosing different density material for the inner shell surface. Experiments to date have concentrated on a target design which undergoes significant acceleration during the laser pulse, leading to dominance of Rayleigh-Taylor growth from the ablation surface. Subsequent experiments will use a modified target design which minimises the acceleration period, allowing the study of shock-induced Richtmyer-Meshkov growth during the coasting phase, and Rayleigh-Taylor growth during the stagnation phase. Here we will concentrate on the calculational predictions using various radiation hydrodynamics codes. The consequences of using direct laser illumination rather than radiative drive (as on NOVA) will be discussed.

1. Introduction

The need to perform mix experiments on a laser facility, rather than relying on traditional techniques (such as provided by shock tubes), is compelling. Shock tubes and rocket-rigs access a near-incompressible regime, where boundary effects, diaphragm interactions, surface tension and immiscibility could compromise the inferred growth characteristics. Mix models have traditionally been normalised to such experiments and idealised 3D fluid code calculations[1]. In the application of the results to the high temperature plasma regime relevant to ICF, the effects of compressibility, miscibility, density gradients, convergence, plasma physics, radiation-induced chunk ablation, radiative modification of the shock behaviour, preheating of the unstable interfaces, and the order of transition between unstable phases are all potentially important issues to be considered. Extensions of the models to include the above physics are questionable and clearly not in general based on experimental evidence. In terms of convergence effects, which are expected to be important, few data exist and are either qualitative, or concentrate on the weakly non-linear growth of macroscopic imposed modes[2], or are confined to the incompressible shock tube regime.

Recent high resolution 3D RT calculations have highlighted significant (~ factor 2) discrepancies with available (incompressible, immiscible) data, possibly due to the regime in which the experiments have been performed, the systematic effects of non-ideal initial conditions, or to limitations in the calculations[3]. Similarly, a better understanding of RM growth requires compressible experiments (for the early time shock transit phase) and extended measurements of the post-shock subsonic flow in which a weak power law growth with time is predicted. A wider experimental base, stretching into a more relevant parameter space, is clearly required. Laser hohlraum driven shock tubes are able to access a high Mach number (compressible) plasma regime and have been used in planar geometry to provide mix growth-rate measurements[4,5]. This has produced apparently good quality data, often in reasonable agreement with post-shot calculations, although with interesting discrepancies between the various experimental results, particularly for RM growth. Discussions about the causes of these discrepancies are ongoing and again highlight the need for further data using a systematically different approach.

Experiments on the OMEGA facility were therefore proposed by AWE to provide a novel vehicle for convergent geometry, compressible, potentially turbulent plasma mix experiments. These would make use of that laser's ability to provide a symmetric illumination onto a cylindrical target with dimensions roughly a factor-2 greater than achievable on NOVA, with greater diagnostic access to the target, but with laser rather than x-ray drive.

2. HELEN Experiments

The HELEN experiments were performed in planar geometry, using a cylindrical ‘shock tube’ mounted on the side of a laser-heated hohlraum target. As shown in Figure 1, radiation from this hohlraum drives a shock from a high density foam region into a lower density region, the two being separated by a well characterised, randomly rough interface. The tube is 400 µm in diameter and 1 mm in length, with the high density region being 200 µm long and the low density region 800 µm long. The central 300 µm diameter of the interface is coated with a thin layer of gold to act as a highly opaque tracer, allowing radiographic determination of the width of the mix region while avoiding complications due to edge effects. Two point projection radiographs are obtained for each target, typically separated in time by 5 ns.

A detailed description of the target design and experimental technique has been published previously, together with preliminary results[6].

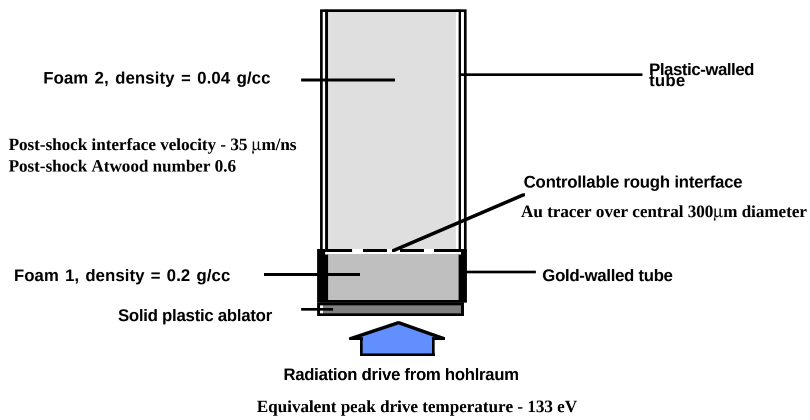

Figure 1 : Schematic of the HELEN R-M Target

Recent data have extended the range of measurements, so that the development of the mix region can be followed over timescales of tens of nanoseconds, corresponding to interface displacements of over 600µm. A sequence of experimental radiographs is shown in Figure 2, at times of 17, 24, and 29 ns. In the first image the gold tracer can clearly be seen as a distinct opaque region over the central region of the tube. As the interface moves up the tube, the width of this layer is seen to grow, with a corresponding decrease in contrast relative to the background foam as the opaque material is dispersed through the mix region.

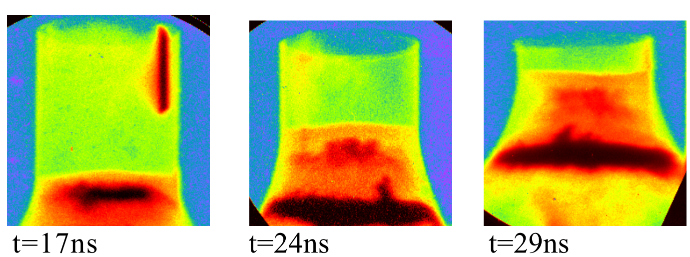

Figure 2 : Series of radiographs from the HELEN R-M experiment showing the evolution of the mix region

In comparing the experimental data with predictions from turbulent mix model calculations, Figure 3 plots mix width as a function of interface displacement, in an attempt to remove shot-to-shot variations in displacement due to laser energy fluctuations. The calculation shown as a solid line is the standard implementation of Youngs’ mix model in 1D, starting from a truly random surface, while the dashed line is the model in which a dominant wavelength, based on the target characterisation data, can be defined in the initial conditions of the problem. In the latter calculation it can be seen that the early time growth is more rapid due to the linear growth of the defined mode, although this soon saturates, and the late time growth rates are identical. This late time growth rate is in good agreement with that obtained from analysis of the pairs of points corresponding to the two radiographs on any given shot. These two calculations effectively form lower and upper bounds on the predicted mix width for the dataset as a whole, although more detailed comparisons can be made for each individual shot.

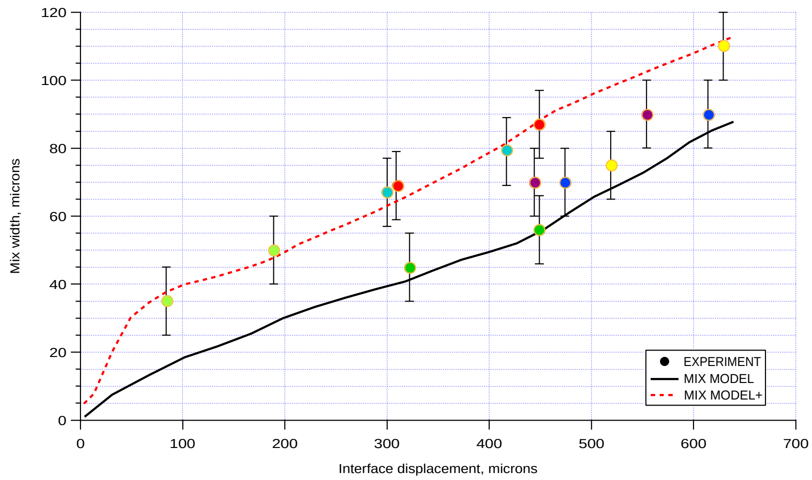

Figure 3 : Comparison of the measured mix widths with 1-D mix model predictions

3. OMEGA Experiments

3.1 Experimental Design

It is obvious that the complexities associated with laser-plasma interactions are unwelcome in a mix experiment. However, the benefits associated with the large targets and good diagnostic access call for the effort to be made to pursue this approach. Through the use of an impulsive drive (laser pulse length < shock transit time through the pusher) and with a sufficiently thick target that the instabilities present at the ablation front are hydrodynamically decoupled from the inner pusher surface, it should prove possible to produce a sufficiently clean experiment. LANL are currently investigating the level of instability growth arising from the nonuniform laser interaction and the imperfect target surface in order to determine the feasibility of performing linear/non-linear RT growth rate measurements of imposed sinusoidal monomodes and multimodes on the inner and outer pusher surfaces[7,8]. These data will complement the AWE campaign, which is biased towards measuring the characteristics of mix evolution arising from a randomly rough surface, growing due to non-linear/turbulent RM/RT instabilities at the inner pusher surface. Through these studies we hope to better understand the influence of the rough DT ice layer on the performance of NIF capsules.

The laser-target illumination configuration has been designed at LANL to provide a constant flux over the central section of the target. This results in a localised, well-defined cylindrical implosion, which can be diagnosed through the use of a radiographically opaque tracer placed at the inner pusher surface in this central section. The lower laser intensities outside of this region result in an 'hour-glassing' of the target which serves to keep the diagnostic line of sight open during the implosion.

In order to test the diagnostic sensitivity to variations in mix evolution, a pair of precursor mix experiments were performed. These used a thin ablator to access an acceleration-dominated implosion, where feed-through of instability growth from the ablation surface would dominate the mix at the inner pusher surface, but provide an assured high level of growth. A variation in susceptibility to mix was achieved by changing the Atwood number of the pusher-foam interface by altering the material (and thus density) of the final section of the pusher. For the 'low-mix' target a chlorinated plastic layer was chosen (density ~ 1.4g/cc), and for the 'high mix' target a gold layer (density = 19.3g/cc). The foam density was chosen to be 0.06g/cc to allow reasonable convergence, whilst still providing enough back-pressure to allow the targets to stagnate at a high enough radius that the radiographic resolution remained sufficient.

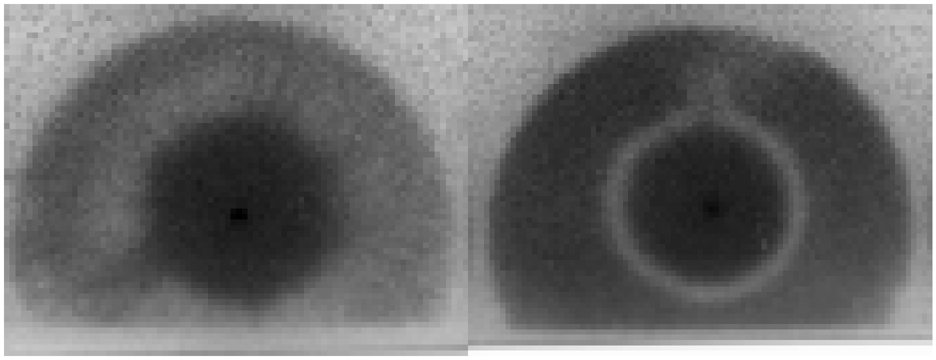

Figure 4: Radiographs from precursor high mix (Au tracer, left) and low mix (CHCl tracer, right) experiments. 16 frames spanning roughly 1 ns are obtained in each experiment.

The data obtained (figure 4) show the significant potential of these experiments to measure time-resolved mix width evolution. The implosions are highly uniform, with a high level of contrast between foam, marker layer and ablator. With appropriate choice of radiographic energy, the areal density distributions within the mix regions could be extracted from the data. It is conceivable that future extensions to the diagnostic might allow spectroscopic discrimination of individual material distributions. Indeed, a principal benefit of the open nature of a direct laser-irradiated geometry is the wide diagnostic access provided. This is illustrated by the range of measurements fielded on these precursor shots[8].

Given the encouraging performance of the diagnostics in the precursor experiments, a design for a well defined mix experiment was pursued. The acceleration phase of the implosion had to be minimised to avoid the coupling of instabilities at the ablation front with the inner pusher (as happens in the experiments to date). An impulsively driven implosion would minimise this phenomenon and allow the growth of RM mix during a coasting, convergent phase to be monitored, followed by deceleration-induced RT growth during the stagnation phase. These experiments would thus complement the wealth of data obtained on acceleration-induced RT growth which is applicable to the early stages of an ICF implosion. An experiment was therefore designed using a square pulse shape to generate a strong shock and with a pulselength equal to the shock transit time through the pusher, to provide maximum impulse to the target.

As before, variation in the density of the inner pusher region would be used to provide the variation in Atwood number, using gold and chlorinated plastic ($C_8H_6Cl_2$; density = 1.42g/cc). The thickness of these layers was chosen by performing mix calculations to determine the areal mass of neighbouring material consumed within the mix region, with the criterion that the layer thickness should significantly exceed this value. An upper bound on the layer thickness is placed by the diagnostic field of view, as the entire layer is required to be imaged. Layer thicknesses of 1µm Au and 4µm CHCl were determined to be acceptable, with sufficient CH ablator to result in equivalent overall pusher areal densities and to ensure an impulsive drive would be obtained.

The radius, velocity and acceleration history of the 'high mix' target predicted using this methodology are shown in figure 5.

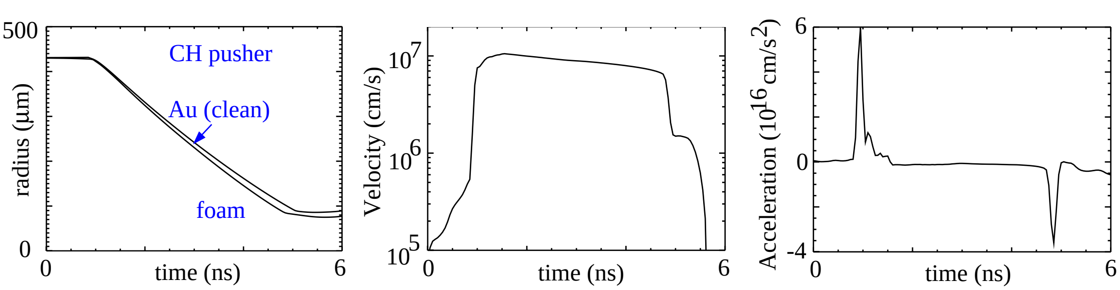

Figure 5 : Radius, velocity and acceleration history for the high mix (Au tracer) cylinder target

These graphs demonstrate the well defined nature of the interaction. There are essentially 4 phases :

a low-level preheat phase (t<1ns)
strong shock (t~1ns)
stable coasting (1<t<5ns)
deceleration from the first and second bounce shocks (t~5-5.5ns)

The principal diagnostic to be used will be a 2D gated x-ray imager. For perfect instrumental resolution, the images produced by this diagnostic are predicted in figure 6. For comparison to data, it is important to take account of a wide variety of other factors : parallax, temporal blurring, spatial resolution, photon statistics, pinhole diffraction and end effects in the hourglassed target. These will be performed post-shot.

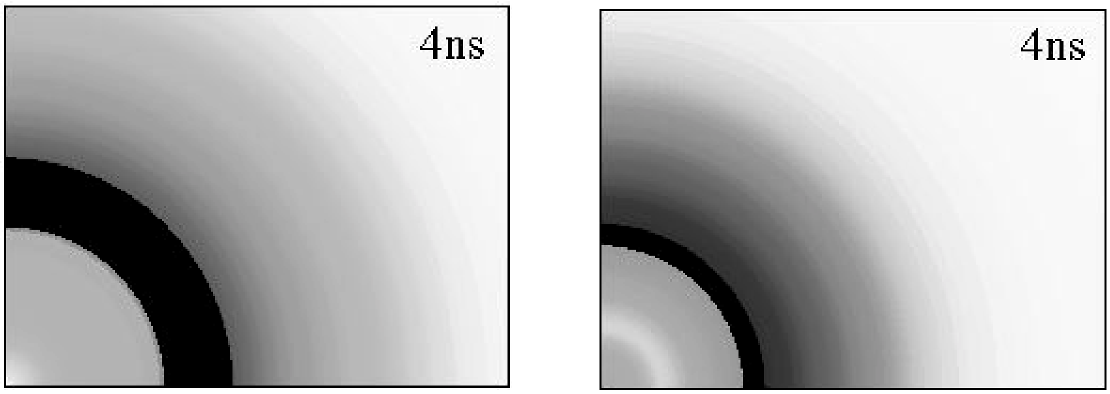

Figure 6 : Ideal simulated radiographs of high mix (Au tracer, left) and low mix (CHCl tracer, right) cylinder targets

The derivation of suitably quantitative information on mix growth rates will require substantial experimental time and development. Thus it is intended that shots over the next two years will concentrate on this goal.

4. Conclusions

Experiments on turbulent mix development in the compressible plasma regime are necessary to validate the performance of mix models, which have been normalised to idealised 3D fluid code calculations and near-incompressible shock tube experiments, for use in realistic applications such as ICF. Data from a planar 'plasma shock tube' experiment on the HELEN laser have shown good agreement with model predictions of growth rate. Experiments are now being performed on an experiment in convergent geometry on the OMEGA laser. A target design has been produced which ostensibly minimises the effect of ablative RT growth (and consequent laser-plasma surface interaction phenomena) and isolates an RM-unstable coasting phase and an RT-unstable deceleration phase. Precursor data have demonstrated that good quality, high resolution data can be achieved on OMEGA, and a series of mix measurements will now commence.

Acknowledgements

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